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Micro-beamer based on MEMS micro-mirrors and laser light source

C. Winter[1], L. Fabre[1], F. Lo Conte[1], L. Kilcher[2], F. Kechana[2], N. Abelé[2], M. Kayal[1]

[1]*EPFL, Electronics Laboratories, Lausanne, Switzerland, maher.kayal@epfl.ch*

[2]*LEMOPTIX SA, Ecublens, Switzerland, nicolas.abele@lemoptix.com*

Abstract

This paper presents a complete portable laser-based projection system using two one-dimensional magnetic actuated MEMS linear scanning micro-mirrors. Dedicated high speed electronics was developed to drive the MEMS, detect the mirror scanning position at any time and synchronize the two mirrors and the laser pulsation. The achieved projection system head is 3 cm^3 and is able to project static images and videos with projection size of 50 cm diagonal at 50 cm distance with 32x32 px resolution, the resolution is only limited by current optical setup. The circuit building blocks itself can project image with resolution up to QVGA (320x240 px), suitable for information display applications.

Keywords: MOEMS; scanning mirror; micro-projector; laser scanning; resonant mirror; magnetic actuation

1. Introduction

MEMS scanning micro-mirrors were developed using various actuation techniques, including thermal, electrostatic, piezoelectric and magnetic. The initial technology choice strongly depends on the applications and the required performances in terms of scanning speed, scanning angle, shock resistance, power consumption and packaging compatibility. In this work, magnetic actuated MEMS micro-mirrors have been developed for the laser scanning projection purpose. Design characteristics and achieved performances of the magnetic MEMS are presented. MEMS-dedicated driving electronics and complete digital and analog electronics circuit for projection purpose are also described.

2. MEMS scanning micro-mirror

2.1. Magnetic mirror actuation

For mobile device application, magnetic actuation offers several advantages in terms of: CMOS-compatible operating voltage, making it compatible with any mobile-type battery, large scanning angle, high frequency operation, good scanning linearity and good mirror planarity, mandatory for high image projection quality. The developed MEMS mirror is composed of a suspended mono-crystalline structure, symmetrical anchored on both sides. A magnetic field is created by an external permanent magnet and the actuation principle is based on Laplace force which is applied on the edges of the mirror, along a metallic coil, when a current is flowing [1], as shown in Fig. 1.

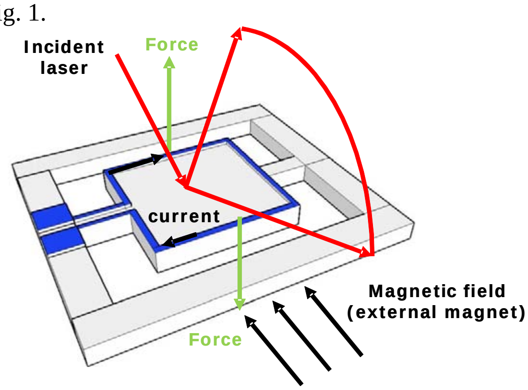

Fig. 1 MEMS mirror magnetic actuation principle

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2.2. MEMS scanning mirror design, optical and mechanical performances

A specific MEMS micro-mirror design was developed to achieve both high frequency of 17.2 kHz and large scanning angle of 40 optical degrees for a reflective scanning surface of 1 mm side (Fig.1). The mirror motion follows an un-damped forced harmonic oscillator characteristic and its mechanical resonant frequency depends on anchors and mirror dimensions [2], according to the following equations:

$$\omega_0 = \sqrt{K/J_r} \tag{1}$$

Where J_r is the moment of inertia of the mirror and K its rigidity, defined as:

$$J_r = \tfrac{1}{12} Y_m^3 H_m X_m \rho_{si} \quad \text{and} \quad K = W\frac{E_{si}}{2l(1-\upsilon)} \tag{2}$$

Where ρ_{Si} is the silicon material, and H_m, X_m, Y_m *are* respectively the thickness, width and length of the mirror, E the silicon Young's modulus, v the Poisson coefficient, l the torsional beam length and W a form factor related to the width and thickness of the torsional beam [3]. The mirrors were also designed to sustain acceleration of 2000 g, key requirements for handheld mobile projection application. The fabrication process was optimized in parallel to the MEMS design to achieve a fabrication yield greater than 95%, resulting in the MEMS mirror shown in Fig.2. Deflection angle of 40 degrees on a high frequency 17.2 kHz mirror was achieved for a voltage of 4 V.

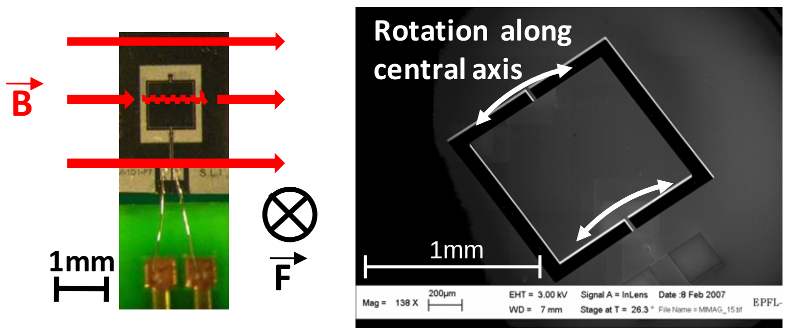

Fig. 2 Left) PCB-mounted MEMS 1D scanning micro mirror, Right) SEM closer view of the MEMS showing the central rotation axis

2.3. Laser micro-projection based on MEMS scanning mirrors

The micro-beamer uses two single-crystal silicon MEMS micro-mirrors as scanning deflectors in order to project a two-dimensional image. The image is projected by scanning the laser beam through the first mirror, and then reflected to the second mirror, placed perpendicularly to the first one [4-5]. The image quality is mainly dependent to the scanning frequency of the mirror, mirror scanning angle and laser spot size. Indeed, higher scanning speed results in higher number of scanned lines for a given time. Moreover, larger scanning angle results in larger projected image and smaller laser spot size enables to increase the number of projected pixels for a given surface. Mirror flatness during actuation should also be maintained, to avoid any optical distortion, therefore the MEMS mirror was mechanically designed to achieve a flatness in scanning operation greater than λ/10 in the visible range.

The complete projection system head of Fig. 3 is less than 3 cm^3 and is composed of a basic laser source in TO-56 package and two one-dimensional MEMS mirror. The image is projected in a pixel-by-pixel by pulsing the laser source at high frequency.

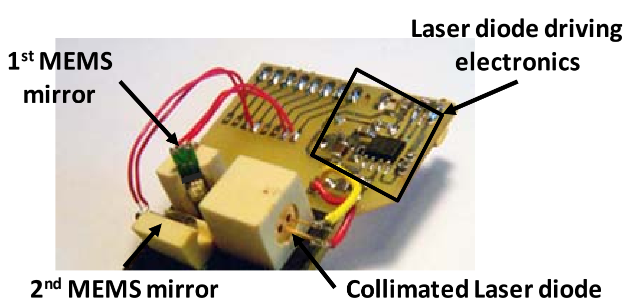

Fig.3 Projection head including two 1-D MEMS micro-mirror, laser diode source and driving electronics

3. Electrical behavior of the mirrors, projection system design and performances

3.1. Mirrors excitation and position measurement

The mirrors are operated at their natural mechanical resonances. The electrical response of the MEMS, to an AC signal actuation, is originally measured in this work via a mutual induced voltage created by the motion of the driving coil in the fixed magnetic field, and is traduced by a change in the mirror impedance of 200 mΩ peak at around 19 Ω (Fig. 4). This technique was used to automatically lock the actuation frequency of the mirror and determine its position at any time. The induced voltage U_{ind} can be expressed with equation (3) and (4) depending on the magnetic field B, the width and length of the coil W and L and the maximum mechanical angle α_{max}. As the coil moves in a given magnetic field, the induced voltage is only depending on the variation of the size of the surface which is crossed by the field and this change only depends on variation of the mechanical angle of the mirror. The induced voltage is then a function of the speed of the mirror and can easily give the position by integration.

$$U_{ind} = -\frac{d}{dt}\Phi(t) \ \ with \ \ \Phi(t) = \int B\,ds = B.s(t) = B.W.L.\sin(\alpha_{\max}).\sin(\omega t) \qquad (3-4)$$

We have then two significant results: We can determine the exact working frequency by scanning a set of frequency around the theoretical designed frequency and seeking the most amplitude of the induced voltage which is a consequence to the biggest mechanical motion. This is very interesting in a production point of view because the final projector is less sensitive to production variation and can automatically trim itself on startup to always obtain the best projection results. The second point is that we have made a position sensor directly in the mirror itself and we can determine its position at any time. As seen in Figure 4, the optical scanning angle of the MEMS mirror is directly dependent to the applied signal, and due to the magnetic actuation, high linearity dependence between the two parameters can be achieved.

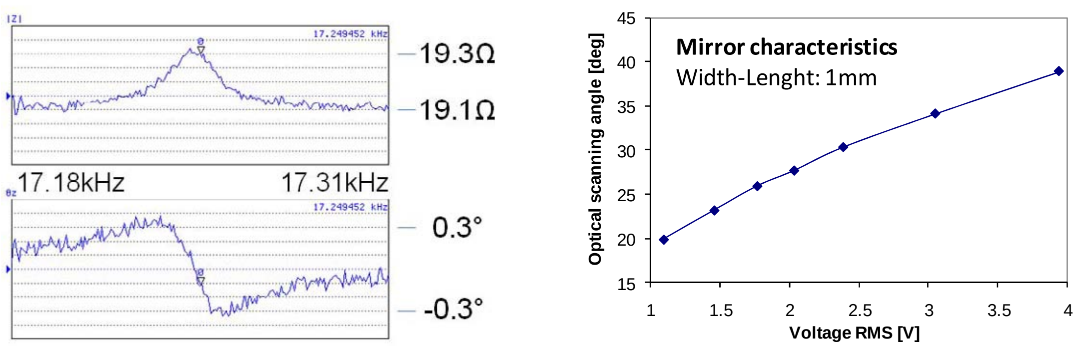

Fig 4 Left) Impedance measurement of the driving coil in the mirror versus frequency. The natural mechanical resonant frequency of the mirror is at 17.25kHz, Right) Optical scanning angle versus actuation voltage

3.2. Projection system : electronics building blocks and performances

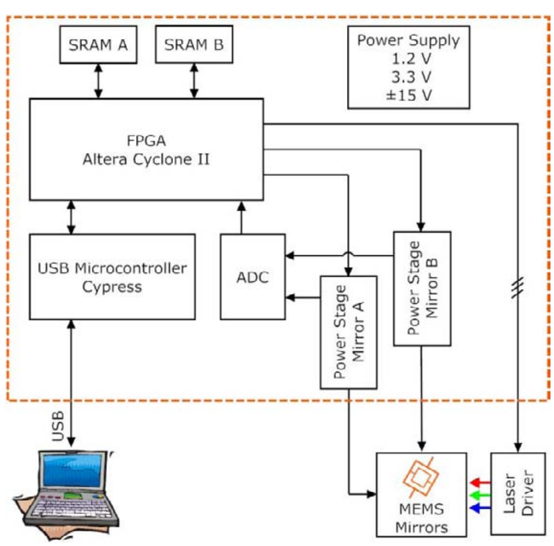

Fig. 5 Projection system control circuit blocs, including the computer interface, image buffering and the MEMS and laser driving scheme

The complete developed projection system (Fig. 5) includes a control electronics circuitry and algorithm able to manage both axis mirrors at their natural frequencies and to synchronize the laser modulation with the mirrors positions at any time. The FPGA-controlled board, working at 60 MHz, is also able to download images from any computer source, store the information and translate the information into MEMS-based projection compatible language and command the laser and the MEMS (Fig. 6). A first projected image with resolution of 32x32 pixels is presented in Fig. 6 and shows already interesting resolution for digits projection and simple information display. Next work objective is to embed high quality optical projection head in order to strongly increase the image quality.

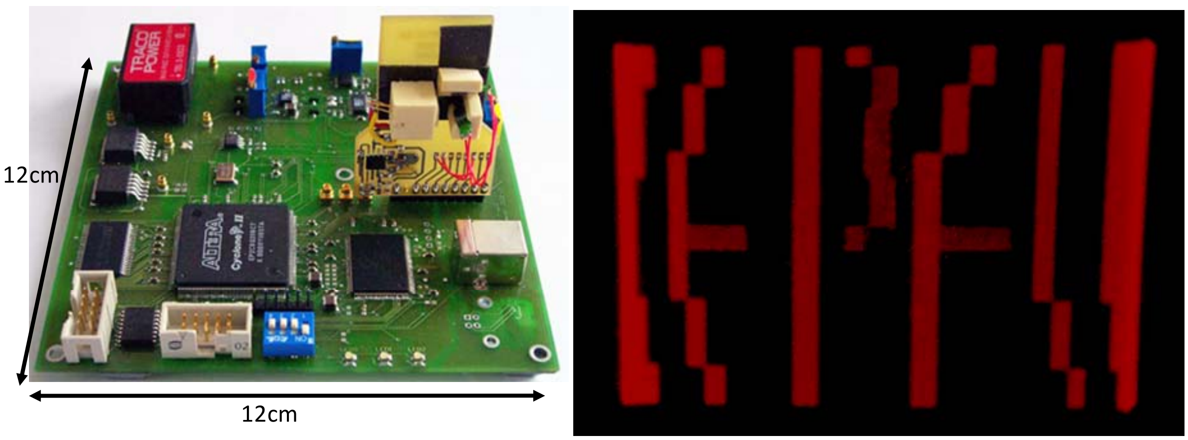

Fig. 6 Left) Complete projection system based on two single axis MEMS scanning micro-mirrors. Right) Projection of EPFL logo with the initial prototype version, with a resolution of 32x32pixels. The image size is 10cm sides at 15cm distance from the source

Conclusion

The complete system, including Micro-beamer based on MEMS micro-mirrors and laser light source, have been realized and demonstrated. The circuit building blocks itself can project image with resolution up to QVGA (320 x 240 px), suitable for information display applications. Further miniaturisation of the complete micro-projection system built around the proposed MEMS scanning micro-mirror platform is under development in CMOS technology. This micro-projector system integrates the MEMS micro-mirror, control electronics, laser light sources and beam combiner optics in a compact, plug-and-play package. This micro-projection system enables the projection of a crisp and bright image onto any curved or flat surface without the need for any focusing or autofocus devices. The resulting screen size is 15 inches (diagonal) at 50 cm distance, with high contrast and brightness levels, enabled by the use of laser light sources which is much brighter than the brightest nowadays beamers.

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